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Thermally developing combined electroosmotic and pressure-driven flow of nanofluids in a microchannel under the effect of magnetic field

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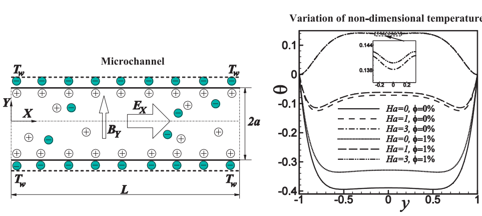
HIGHLIGHTS

- We studied thermally developing magnetohydrodynamic flow of nanofluid in a microchannel.
- Effect of the magnetic field, nanoparticle concentration and agglomeration are investigated.
- Heat transfer decreases with increase in nanoparticle concentration and agglomeration.
- Effect of the nanofluid on system irreversibility is also studied.

GRAPHICAL ABSTRACT



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ABSTRACT

In the present study, the heat transfer characteristics of thermally developing magnetohydrodynamic flow of nanofluid through microchannel are delineated by following a semi-analytical approach. The combined influences of pressure-driven flow, electroosmotic transport and magnetic field is taken into account for the analysis of the complex microscale thermal transport processes. Solutions for the normalized temperature distributions and the Nusselt number variations, considering the simultaneous interplay of electrokinetic effects (electroosmosis), magnetic effects, Joule heating and viscous dissipation are obtained, for constant wall temperature condition. Particular attention is paid to assess the role of nanofluids in altering the transport phenomena, through variations in the effective nanoparticle volume fractions, as well as the aggregate structure of the particulate phases. It is observed that magnetohydrodynamic effect reduces advective transport of the liquid resulting in gradual reduction of heat transfer. Increase in nanoparticle volume fraction shows decrease in heat transfer. Similar effects are observed with increase in aggregate sizes of the nanoparticles. The effect of the nanofluids on system irreversibility is also studied through entropy generation analysis due to flow and heat transfer in the microchannel. Total entropy generation is found to be dominant at the thermally developing region of the microchannel, whereas it drops sharply at the thermally developed region. Presence of nanoparticles in the base fluid reduces the total entropy generation in the microchannel, thereby indicating decrease in thermodynamic irreversibility with increasing nanoparticle volume fraction.

1. Introduction

Microfluidic technology and micro-electro-mechanical-systems (MEMS) have manifold applications in various fields of sciences and engineering, such as heat exchangers, micropumps, chemical

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separation devices, lab-on-a-chip system for drug delivery, biochemical analysis and biomedical diagnostics. All these devices and instruments involve fluid flow and heat transfer in microchannels. Transport phenomena at the microscale exhibit distinctly different characteristics, as compared to the macroscale transport behaviour, primarily due to the interfacial effects such as electric double layer (EDL) (Manz et al., 1990; Probstein, 1994; Gad-el-Hak, 1999). The electric double layer is formed due to the interaction of ionized solution with static charges on dielectric surfaces. On application of an external electric field, the mobile ions in the EDL region will move, resulting in a bulk liquid motion via viscous effect. This is known as the electroosmotic flow (EOF) (Rice and Whitehead, 1965; Probstein, 1994).

The electroosmotic phenomenon was first demonstrated by Reuss (1809) in an experimental investigation using porous clay. Owing to their diverse applications, the study of EOF has received a great deal of attention (Han and Craighead, 2000; Zeng et al., 2001; Yang et al., 2001; Reyes et al., 2002; Erickson and Li, 2004). Many scholars have investigated the hydrodynamics and thermal transport phenomena in electroosmotically driven flow in microchannel (Burgreen and Nakache, 1964; Levine et al., 1975; Patankar and Hu, 1998; Yang et al., 1998; Dutta et al., 2002; Maynes and Webb, 2003a, 2003b; Horiuchi and Dutta, 2004; Chakraborty, 2006; Rawool and Mitra, 2006; Zade et al., 2007, Chen et al., 2013) with and without considering the effects of axial pressure gradients. Maynes and Webb (2003) investigated thermally fully developed flow situation in microchannels for pure electroosmotic and combined pressure-driven and electroosmotic flows. Horiuchi and Dutta (2004) provided analytical solutions for temperature distribution and Nusselt number for thermally developing electroosmotic flows through straight microchannels. In recent studies, Dey et al. (2011, 2012) analysed the thermal transport characteristics for both thermally fully developed and thermally develop ing flows in microchannel in the presence of thick electrical double layer.

In many practical engineering applications, internal heat generation associated with electroosmotic microflows pose a serious problem due to the significant side effects arising out of the temperature rise of the microfluidic system (Knox, 1988; Gobie and Ivory, 1990; Swinney and Bornhop, 2002; Xuan and Li, 2004). Therefore, thermal management of microscale devices has become more important and challenging due to the need for fast removal of heat and maintaining uniform temperature distributions in such small devices. This can be achieved by using nanofluid as the working fluid in the microchannel. Nanofluid is a mixture of base fluid and suspended nanoparticles and is characterized by high effective transport coefficients (Choi, 1995, 2009; Ganguly et al., 2009). Several researchers have demonstrated the superior heat transfer performance of nanofluids through experimental and numerical studies (Keblinski et al., 2005; Wang and Mujumdar, 2007; Kakác and Pramuanjaroenkij, 2009). The assessment of thermal transport characteristics in electroosmotically driven flow of nanofluids in microconduits, on the other hand, is rather rarely found in the literature. Jang and Choi (2006) studied the cooling performance of a microchannel heat sink with nanofluids. Although electroosmotic effects were not considered, their study demonstrated improvement in heat transfer for pressure driven microflows. Li and Kleinstreuer (2008) compared the thermal performance of CuO-water nanofluid and pure water in a trapezoidal microchannel. Chakraborty and Roy (2008) developed an analytical model to assess the role of nanofluids in influencing the convective transport mechanisms in a microchannel. A thermally developing and hydrodynamically developed transport model was considered in the study (Chakraborty and Roy, 2008). As such, the intricacies of microscale transport characteristics of nanofluid flow considering both the effects of Joule heating and viscous dissipation are still not fully understood. In addition, consideration of magnetohydrodynamic transport in thermally developing combined electroosmotic and pressure-driven nanofluid flow in microchannel is also not reported till date. On the other hand, in recent years, use of magnetic field as flow actuation mechanism has assumed great importance in wide spectrum of micro/nanofluidic applications (Jones, 1995; Jang and Lee, 2000; Zimmerman and Parada, 2006; Chakraborty and Paul, 2006; Das et al., 2012; Nguyen, 2012; Turkyilmazoglu, 2012). Therefore, in order to explore the full potential of such magnetically induced flow actuation mechanism, it is imperative to study the associated thermal transport by considering the essential physics of microscale transport phenomena.

The present paper delineates, for the first time, the effect of nanofluid on thermally developing magnetohydrodynamic flows through microchannel, by considering combined effects of externally applied pressure gradient and electroosmosis. The essential features of electro-magnetohydrodynamic flow and heat transfer characteristics are explained through the variations of the non-dimensional flow velocity, non-dimensional temperature and Nusselt number, over physically permissible ranges of various involved parameters, by adopting an analytical approach. Parametric studies have been undertaken to examine the influence of magnetic strength, volume fraction of the dispersed nanoparticles, and particle agglomeration on the overall thermofluidic transport in microchannel. The theoretical analysis of the involved physical problem attempts to capture the intricate features of microscale thermal transport processes, arising out from the interplay of the imposed magnetic field and spontaneous electrokinetic effects, in the presence of Joule heating and viscous dissipation. The present study also describes the alterations in the entropy generation for such systems for better design of pertinent microfluidic devices. The combined model is, therefore, expected to provide valuable guideline towards thermodynamic idealization of a microfluidic system through minimum entropy generation.

2. Mathematical model

2.1. Physical problem

We consider thermally developing electroosmotic transport of Al_2O_3–water nanofluids in a parallel plate microchannel, in the presence of imposed pressure gradient and external magnetic field. The microchannel is of height $2a$ and length L, and its width is much larger than either of these dimensions. The channel centreline is oriented along the x-axis (see Fig. 1). An external electric field and a pressure gradient are applied along the horizontal axis of the channel, which provides driving force for flow. It may be noted here that in the present case, the flow is generally very slow in nature with very low Reynolds number, $Re \ll 1$ (Nguyen, 2012; Bruus, 2008). In addition, an external uniform magnetic field is applied along the transverse direction to the flow so that the resultant magnetohydrodynamic transport

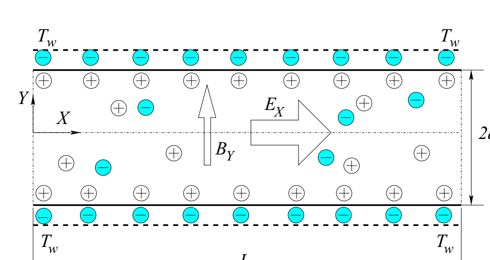

Fig. 1. Schematic diagram of the problem domain.